EXPERIMENTAL STUDY ON THE EFFECTIVENESS OF STRENGTHENING REINFORCED CONCRETE SLAB-COLUMN CONNECTIONS USING CFRP SHEETS

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Abstract

This paper presents an experimental study on the effect of externally bonded carbon fiber-reinforced polymer (CFRP) sheets on the punching shear behavior of interior slab-column connections. Two square slabs with a concentric column were fabricated, measuring 1200 × 1200 × 80 mm for the slabs and 200 × 200 mm for the column. One specimen served as an unstrengthened control specimen, while the other specimen was strengthened using CFRP sheets. The specimens were simply supported along their edges and subjected to punching tests, with the vertical load applied through the central column. The experimental results revealed that the application of CFRP sheets significantly improved the performance of the slab-column connections. The strengthened slab exhibited a 16.3% increase in punching capacity compared to the control specimen. Additionally, a calculation was conducted to determine the punching shear strength of the test specimens, taking into account the interaction between shear and flexural capacities in a two-way flat slab. This calculation provided a deeper understanding of the impact of CFRP sheet strengthening on the enhancement of the strength of the slab-column connections.

Keywords: two-way flat slab; punching; strengthening; CFPR sheets; slab-column connection.

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1. Introduction

Reinforced concrete (RC) flat slabs are widely used in various structures, including buildings, parking garages, and bridges. These slabs offer the advantage of providing more vertical clear space due to the absence of beams, as they are directly supported on columns. However, one significant limitation of this system is its vulnerability to punching shear failure near concentrated loads or supporting columns [1, 2]. Punching shear failures in flat slabs are characterized by their brittle nature, occurring at relatively small deflections. The punching strength of slabs can become insufficient due to various factors, including changes in building use, the need to install new services requiring openings in the slabs, reinforcement corrosion, and construction or design errors. These factors can lead to a reduction in the structural integrity and load-bearing capacity of flat slabs.

Retrofitting slab-column connections to increase their punching shear capacity is crucial for ensuring the safety and performance of structures. Strengthening and stiffening slab connections are primary objectives aimed at enhancing the overall structural performance and ultimate load-carrying capacity. In the existing literature, several researchers have extensively investigated various methods to strengthen interior slab-column connections against punching shear failure. These methods include the use of steel plates and bolts, transverse prestressed reinforcement, and the application of fiber-reinforced polymer (FRP) composites externally bonded to the tension face of the slab [3–11].

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Regarding the use of CFRP sheets as strengthening techniques, it is indeed a suitable solution for reinforced concrete structures to enhance their performance. CFRP sheets offer several advantages, such as high strength-to-weight ratio, corrosion resistance, and ease of installation. When externally bonded to concrete elements, CFRP sheets can provide additional flexural and shear strength, improve stiffness, and enhance the overall structural behavior [12–18]. Several researchers have conducted studies on the punching shear behavior of RC flat slabs externally strengthened with carbon fiber-reinforced polymer (CFRP) sheets Wang and Tan [13], Ospina et al. [14], Sharaf et al. [15], Soudki et al. [16], Chen et al. [17] are among the researchers who have investigated this topic. The main variables in these studies were the amount and configuration of CFRP strengthening. It is worth noting that the FRP reinforcement systems used in the previous research work varied in terms of their mechanical properties, such as fiber type, orientation, volumetric ratio of the fiber to the resin, and manufacturing process. This diversity in CFRP systems highlights the need for a comprehensive assessment of the effectiveness of using FRP reinforcement in rehabilitating or strengthening slab-column connections. Although these studies have provided valuable insights into the behavior and performance of CFRP-strengthened slabs, further research, and a more extensive database are necessary to fully evaluate the effectiveness and optimize the use of CFRP sheets in slab-column connection strengthening.

This study aims to investigate the effect of externally bonded carbon fiber-reinforced polymer (CFRP) sheets on the punching shear behavior of interior slab-column connections. The experimental study was carried out at the Laboratory of Testing and Construction Inspection, Ha Noi University of Civil Engineering. The findings of this study indicated that strengthening slab–column connections using CFRP sheets increased flexural stiffness and significantly improved the punching shear strength.

2. Experimental research

2.1. Specimen and material properties

The experimental program involved two RC interior slab-column connections with identical geometrical configurations and steel reinforcement details, as shown in Fig. 1. The overall dimensions of

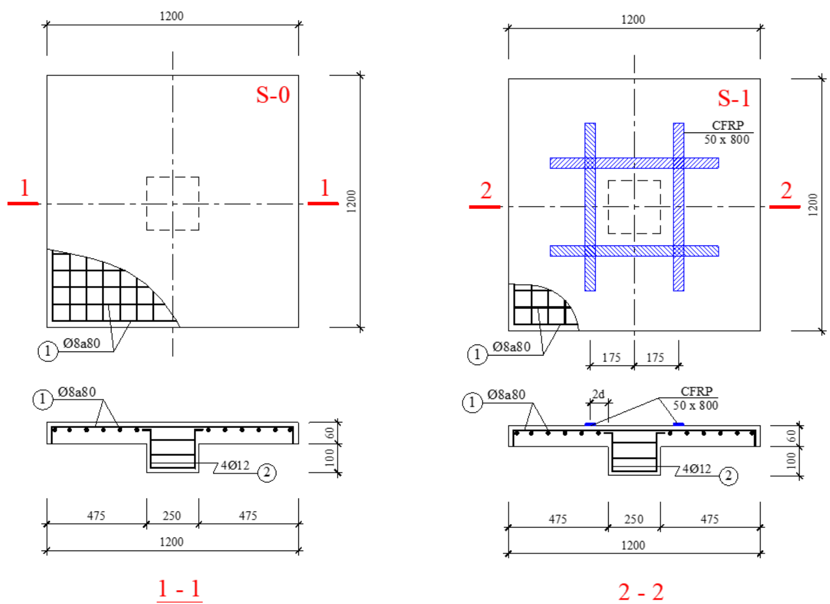


Figure 1. Details of two test specimens

the slabs were 1200 × 1200 mm with a thickness of 60 mm. Each slab was reinforced with a single layer of ∅8 deformable steel bars, spaced 80 mm apart (center-to-center) in both directions. A central column stub, measuring 250 × 250 mm, was cast together with the slab. The concrete cover provided a thickness of 20 mm. The test specimens consisted of two samples: one specimen, named S-0, served as an unstrengthened control specimen, while the other specimen, S-1, was externally strengthened using CFRP sheets bonded to the tension face of the slab. The CFRP sheets were cut into strips measuring 800 mm in length and 50 mm in width. These CFRP strips were positioned in an orthogonal orientation and placed at a distance of 2d from the face of the column, as prescribed by Eurocode 2 (EN 1992-1-1) [2]. According to Eurocode 2, this distance corresponds to the critical shear section for punching shear in RC slabs. In this case, the value of d, which represents the effective depth of the slab, is equal to 45 mm.

Table 1. Concrete mix proportioning (kg/m^3)

Cement (kg)	Sand (kg)	Crushed stone (10-20 mm) (kg)	Water (kg)	Water/Cement (W/C) ratio	The 28-day compressive strength (MPa)
350	680	1240	175	0.5	23.5

In Table 1, the mix proportions for concrete are provided along with the achieved 28-day compressive strength. The compressive strength was determined using three standard cylinder samples with dimensions D × H of 150 × 300 mm. Fig. 2 illustrates a compressive test in progress. The steel bar reinforcement had a diameter (∅) of 8 mm and yield strength of 295 MPa.

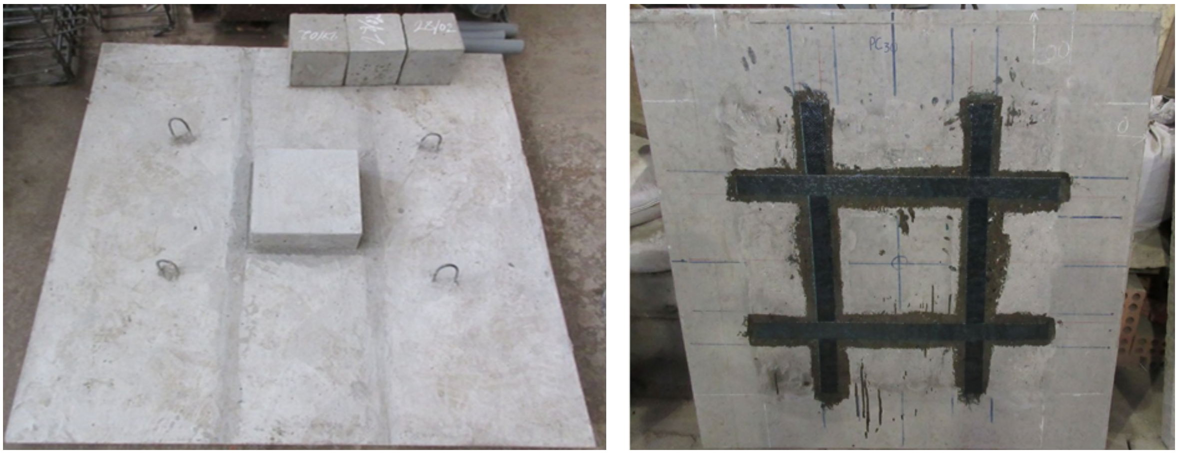
The CFRP sheets utilized in this study were unidirectional. The mechanical properties of the CFRP sheets, as provided by the manufacturers, are presented in Table 2.

Figure 2. Concrete compressive test

Table 2. Mechanical properties for CFRP sheets

Thickness (mm)	Modulus of elasticity (GPa)	Ultimate tensile strength (MPa)	Ultimate deformation (%)
1.0	95.8	521	2.0

Fig. 3 depicts the unstrengthened specimen S-0 and the strengthened specimen S-1. As for the strengthening procedure, before applying the carbon fiber fabric sheets, the specimen's surface was thoroughly cleaned of dust and contaminants using a high-pressure air jet. Next, an epoxy resin was directly applied onto the prepared substrate using a trowel. The precut CFRP sheets, tailored to the desired dimensions, were then placed onto the resin coating. The pressure was applied with gloved hands to ensure proper impregnation of the resin between the fabric's rovings. Finally, a final sealer coat of resin was applied to the exposed surface. The specimens were left to cure for approximately four days before undergoing testing.



(a) S-0 (b) S-1

Figure 3. Images of two test specimens

2.2. *Test setup and instrumentations*

Fig. 4 shows the test setup employed for the experimental investigation, while Fig. 5 illustrates a test in progress. Two specimens were subjected to monotonically increasing loading, with the load applied from the bottom upward, through the column stub. The test specimens were simply supported along all four edges, utilizing a rigid steel frame. This steel frame was placed on the top face of the test specimen (the tensile face) and was connected to the bearing floor through four anchor bolts with a diameter of 32 mm.

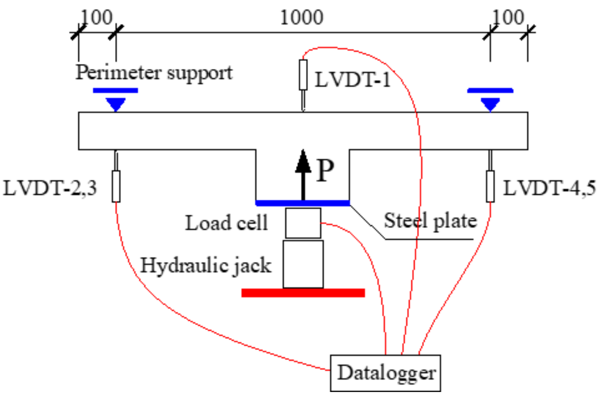


Figure 4. Test setup

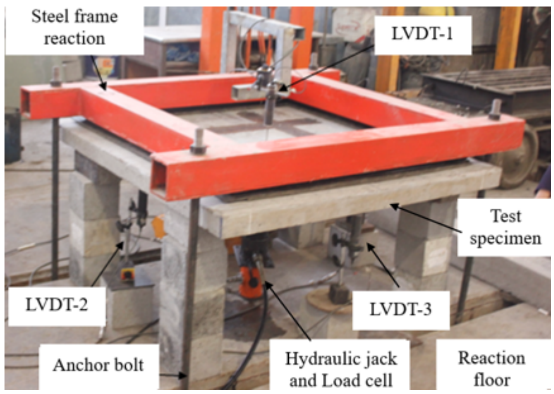


Figure 5. Illustration of a test in progress

In the experimental setup, a hydraulic jack was employed to apply an axial load to the columns. To measure the magnitude of the applied load, an electronic force-measuring instrument, known as a load cell, was utilized. The deflection of the test specimen at the column position was measured using five Linear Variable Differential Transducers (LVDTs). These LVDTs were positioned at specific locations on the test specimen: one at the centroid (LVDT-1) and four at the middle of each of the four edges (LVDT-2, LVDT-3, LVDT-4, LVDT-5). The vertical displacements measured by these LVDTs were denoted as f_1, f_2, f_3, f_4, and f_5, respectively. The formula for determining the deflection of test specimens, f, is as follows:

$$f = f_1 - \frac{f_2 + f_3 + f_4 + f_5}{4} \tag{1}$$

The load cell and LVDTs were connected to a TDS 530 data logger, which facilitated the continuous and automatic recording of the experimental data at one-second intervals. The tests were conducted until the failure of the specimens.

3. Results and discussions

3.1. Failure modes

The mode of failures observed in the control specimen S-0 and the strengthened specimen S-1 were illustrated in Fig. 6.

(a) Control specimen S-0 (b) Strengthened specimen S-1

Figure 6. Photograph of failure of test specimens

For two test slabs, the initiation of flexural cracks on the tension face of the specimens started at an early stage of load application. Cracking first developed in the central region of the slab as fine flexural cracks perpendicular to the direction of tension steel reinforcement. More orthogonal cracks developed and propagated toward the slab edges while the load increased. As the load increased, a series of diagonal cracks formed, starting from near the column corners and extending toward the slab edges and corners. Finally, the diagonal cracks were attached and the two slabs failed in punching shear failure mode, which was sudden and brittle. In Fig. 6, the photographs reveal the punching shear failure plane occurring around the column. For the S-0 specimen, the distances from the face of the column stub to the punching shear plane ranged from 120 mm to 190 mm. The average distance was approximately 155 mm, which is equivalent to 3.4d. As for the S-1 specimen, the average distance was 3.0d (d is the effective depth of the slab).

The comparison between the S-1 specimen and the control specimen reveals notable differences in crack behavior. The S-1 specimen exhibits a higher number of cracks, but these cracks tend to have smaller widths compared to the control specimen. This observation can be attributed to the presence of CFRP strips, which effectively arrest the propagation of cracks and limit their width.

During the punching shear failure, the CFRP strips in the S-1 specimen were pulled away from the specimen, and the concrete cover surrounding them was also removed. This occurred as the truncated concrete cone was pushed through the slab. It is important to note that the CFRP strips did not experience debonding as a result of epoxy or concrete-epoxy bond failure. The failure mode primarily involved the removal of the concrete cover and the detachment of the CFRP strips from the slab.

3.2. Load-deflection relationship

Fig. 7 illustrates the load versus deflection (*P-f*) curves for the two test specimens and Table 3 gives a summary of test results. The load-deflection response can be divided into two stages: the uncracked stage (OA), which represents the elastic behavior before the occurrence of cracking, and the post-cracking stage (AB).

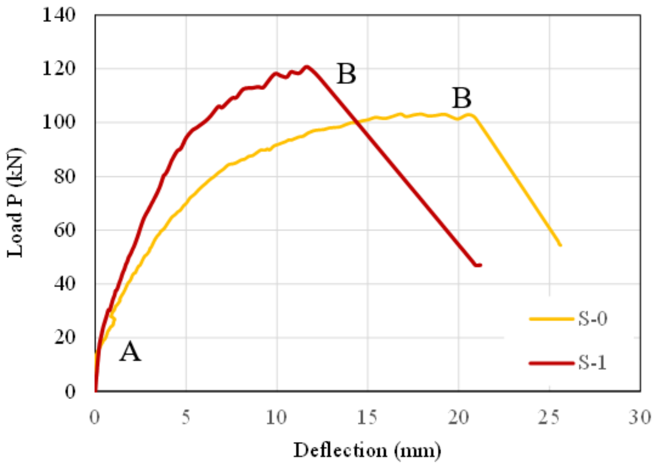


Figure 7. Load-deflection relationship of test specimens

Table 3. Test results

Specimen	Ultimate load (kN)	% increase above control	Deflection at ultimate load (mm)
S-0	102	-	22
S-1	121	16.3	13

Both the unstrengthened and strengthened specimens exhibited similar behavior in the uncracked stage, represented by the O-A portion of the load-deflection curve. This stage corresponds to the elastic behavior of the specimens before the occurrence of cracking. At point A, a change in the slope of the load-deflection curve is observed, indicating the onset of cracking due to bending moments in the slab. During this period, it is important to note that the load-deflection relationship was the same for all S-0 and S-1 specimens. This indicates that, under small loads, the behavior of both the unstrengthened and strengthened specimens was similar and unaffected by the strengthening intervention. The strengthening technique had not yet exerted a significant influence on the overall response during this stage.

The post-cracking stage of the load-deflection curve is represented by the A-B portion. Point B corresponds to the failure of the specimens due to punching shear. At this point, the ultimate load can be determined, indicating the maximum capacity of the specimens. The effectiveness of the CFRP strip in strengthening the specimens is clearly demonstrated in this stage.

It is evident that the overall post-cracking stiffness, calculated as the slope of the *P-f* curve, is significantly greater for the strengthened specimen compared to the control specimen. This indicates that the CFRP strips contribute to an increase in stiffness, enhancing the structural performance of the specimen. Furthermore, the S-1 specimen exhibits a notable increase in punching shear capacity, with a 16.3% increase over the S-1 specimen. This highlights the effectiveness of the CFRP strip in improving the load-carrying capacity and resistance to punching shear failure. In terms of ultimate deflection (deflection at ultimate load) the control specimen exhibits a higher deflection value at the corresponding ultimate load. This result confirms the stiffening effect of the CFRP strips, as the strengthened specimen exhibits less deflection under the same applied load compared to the control specimen.

Overall, the findings highlight the positive impact of CFRP strips in enhancing the performance of the strengthened specimen. The inclusion of CFRP strips increases the flexural capacity of the slab, thereby improving the punching shear capacity as well. This provides a basis for proposing a simplified model for the calculation of the punching shear capacity of strengthened specimens.

3.3. Calculation of punching shear strength of test specimens

The punching shear capacity is affected by flexural behavior because the maximum bending moment usually occurs near the location where the punching shear occurs. The interaction between the shear and the flexure in two-way slabs, in which the flexural strength capacity is considered a parameter in calculating the shear strength, is expressed as follows [19]:

$$P_u = \frac{0.8\left(1+\dfrac{d}{r}\right)bd\sqrt{f_c'}}{1+0.433bd\dfrac{\sqrt{f_c'}}{P_{flex}}} \tag{2}$$

where P_u is the ultimate applied force to cause punching shear failure, d is the effective depth (distance between the center of the tensile reinforcement and the extreme concrete compressive fiber), r is the side length of a square loaded area or width of the column stub, b is the perimeter of column stub, f_c' is concrete compressive strength, P_{flex} is the load applied to cause flexure failure.

For a two-way square slab with one layer of steel reinforcement, and subjected to a concentrated load through the column stub, P_{flex} can be derived using yield line analysis as follows [20]:

$$P_{flex} = 8m\left(\frac{1}{1-r/w} - 3 + 2\sqrt{2}\right) \tag{3}$$

where m is flexural moment capacity per unit width, and w is slab width.

Fig. 8 depicts the schematic diagram used to calculate the flexural moment capacity of the slab. The following assumptions were considered in the calculation: (1) plane-section assumption; (2) slab damage in flexion due to the yielding of the tensile steel reinforcement, while the concrete in the compression zone is broken; (3) the ultimate compressive deformation of concrete, denoted as ε_{cu}, is equal to 0.0035 [2, 21].

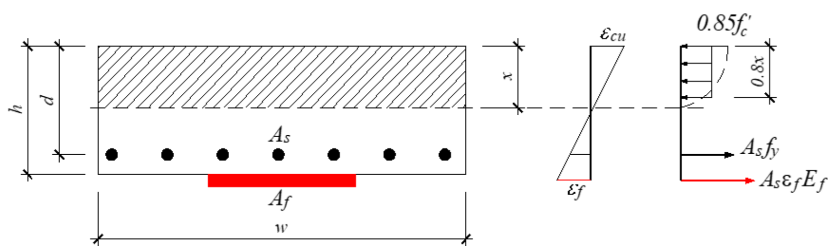


Figure 8. Schematic diagram for calculation of the flexural moment capacity

The height of the compressive zone, x, is determined as follows:

$$0.85f_c'(0.8x) = A_sf_y + A_f\varepsilon_fE_f \tag{4}$$

where A_s is the area of tensile reinforcement of the slab, f_y is the yield stress of the steel reinforcement, A_f is the area of CFRP strips, ε_f is the deformation of CFRP sheets, f_c' is the concrete compressive strength.

The deformation of CFRP sheets is calculated as follows:

$$\varepsilon_f = \varepsilon_{cu}\frac{h-x}{x} \le \varepsilon_{fu} \tag{5}$$

where ε_{fu} is the ultimate deformation of CFRP sheets.

The flexural moment capacity per unit width m can be calculated as follows:

$$m = \frac{1}{w}\left[A_s f_y\left(d - \frac{0.8x}{2}\right) + A_f \varepsilon_f E_f\left(h - \frac{0.8x}{2}\right)\right] \tag{6}$$

Based on the geometrical configurations and steel reinforcement details, along with the known concrete and steel reinforcement strengths, the punching shear strength of the two test specimens can be calculated using the above formulas. Table 4 presents a comparison between the experimental results and the calculated punching shear strength of the two test specimens. The results demonstrate that the calculated values align well with the experimental findings. The computational analysis allows for a deeper understanding of the impact of CFRP sheet strengthening on the increase in punching shear strength of the test specimens. By comparing the calculated and experimental results, it becomes possible to assess the extent to which CFRP sheets contribute to enhancing the punching shear strength of the two-way slabs.

Table 4. Comparison of experimental and calculated punching shear strength of test specimens

Specimens	m (kN.m/m)	P_{flex} (kN)	$P_{u\text{-}calc}$ (kN)	$P_{u\text{-}test}$ (kN)	$P_{u\text{-}test}$ / $P_{u\text{-}calc}$
S-0	9.39	82.0	93.7	102	1.08
S-1	13.1	114.4	110	121	1.10

4. Conclusions

This paper presents the results of an experimental study investigating the effect of externally bonded carbon fiber-reinforced polymer (CFRP) sheets on the punching shear behavior of interior slab-column connections. Based on the findings, the following main conclusions can be drawn:

- The application of CFRP sheets to strengthen concrete slab-column connections is a suitable solution. The use of CFRP sheets significantly improved the performance of the slab-column connection by increasing the punching shear capacity and stiffness of the slab. The experimental results showed an increase of 16.3% in punching shear capacity with the application of CFRP sheets. This enhancement in punching shear capacity is attributed to the increased flexural strength provided by CFRP sheet strengthening.

- The calculation of punching shear capacities of the tested specimens allowed for a deeper understanding of the interaction between shear and flexure in two-way flat slabs, where punching shear is influenced by the flexural strength of the slab. The calculated punching shear capacities aligned well with the experimental results, indicating the reliability and accuracy of the calculation method. This provides valuable insights into the punching shear behavior of slab-column connections and helps in better understanding the interaction between shear and flexure in the two-way slab.

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